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A water marker monitored by satellites to predict seasonal endemic cholera

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Abstract

The ability to predict an occurrence of cholera, a water-related disease, offers a significant public health advantage. Satellite based estimates of chlorophyll, a surrogate for plankton abundance, have been linked to cholera incidence. However, cholera bacteria can survive under a variety of coastal ecological conditions, thus constraining the predictive ability of the chlorophyll, since it provides only an estimate of greenness of seawater. Here, a new remote sensing based index is proposed: Satellite Water Marker (SWM), which estimates condition of coastal water, based on observed variability in the difference between blue (412 nm) and green (555 nm) wavelengths that can be related to seasonal cholera incidence. The index is bounded between physically separable wavelengths for relatively clear (blue) and turbid (green) water. Using SWM, prediction of cholera with reasonable accuracy, with at least two month in advance, can potentially be achieved in the endemic coastal regions.

1. Introduction

Cholera, an acute water-borne diarrheal disease, is a significant global health threat. The ongoing seventh pandemic of cholera, has been reported in over 50 countries (Gleick 2008). Almost all major cholera outbreaks have occurred in the coastal regions, indicating a strong link between coastal environment and cholera (Colwell 1996). Since *V. cholera*, the causative agent of the disease, survives in the natural environment of brackish water and a powerful evidence of new biotypes is accumulating, it is highly unlikely that cholera will be eradicated (Jutla *et al.* 2010). But the disease can rather be controlled, by providing safe drinking water and sanitation facilities in susceptible regions (Akanda *et al.* 2012). Consequently, it is important to develop cholera prediction models that have potential to provide sufficient lead times for enacting effective intervention as well as strengthen prevention efforts.

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Phytoplankton abundance, because of its relationship to zooplankton and the latter with cholera bacteria (Colwell and Huq 2001), as well as ease of estimation over large areas using satellite-derived chlorophyll, has been employed to understand cholera and its coastal connection as well as to determine likelihood of disease outbreaks (Lobitz *et al.* 2000). Space-time variability of phytoplankton abundance over a large oceanic region may provide phenomenological linkage to cholera incidence, but distribution of cholera bacteria depends on a range of coastal ecological conditions including phytoplankton (Tamplin *et al.* 1990), zooplankton (Colwell and Huq 1994), salinity (Singleton *et al.* 1982) and organic material (Worden *et al.* 2006). Results of a previous study (Jutla *et al.* 2012) indicated that chlorophyll has limited association with cholera incidence (correlation coefficient, $r=0.45$) in the Bengal Delta. Chlorophyll algorithms for satellites have been developed, calibrated and validated to estimate greenness, a proxy for phytoplankton abundance, of seawater. Seawater also contains organic matter, detritus, flora and fauna that are not represented by the chlorophyll algorithm, but contribute in growth and proliferation of cholera bacteria (Worden *et al.* 2006). Consequently, it is unlikely that chlorophyll estimates alone can provide a fully operational and feasible prediction of cholera incidence with reasonable accuracy. A combination of satellite measured radiance captures biological growth more extensively than chlorophyll estimates for seawater (e.g., phytoplankton groups: Subramaniam *et al.* 2002; organic matter: Carder *et al.* 1991; harmful algae: Cannizzaro *et al.* 2008). A key objective of this study was to develop an index using a combination of satellite observed wavelength radiance, which has an error of about 5% compared to more than 30% for chlorophyll (McClain *et al.* 1998), that can identify spatial and temporal conditions in coastal regions to help predict cholera incidence with several months lead time. Desired attributes for such an index are: (i) ability to predict cholera incidence with satisfactory accuracy with one to two months in advance; and (ii) applicability over different geographic regions with minimal tuning of parameters.

2. Data

Cholera epidemiological data were collected by investigators at the International Centre for Diarrheal Disease Research, Bangladesh (ICDDR,B). Incidence is recorded as the percent of new cholera patients among a statistical subset of patients selected from a total pool of patients visiting the hospital for treatment during a given week in the Dhaka city of Bangladesh (Hashizume *et al.* 2011). Cholera surveillance data for Mozambique were compiled from cases mentioned in the reports of ProMed (www.promedmail.org; accessed on October 20, 2011). The data were around the capital city of Maputo, Mozambique and were aggregated on monthly scales. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) monthly radiance for five bands (412, 443, 490, 510, 555 nm) at 9-km resolution, were obtained from NASA/Goddard Earth Sciences/Distributed Active Archive Center for a twelve-year period (September 1997- September 2010). The coastal water zone of the Bay of Bengal is defined as the region between 20.0–22.5°N and 88.5–93.0°E. The choice of coastal area in the bay is dictated by the bathymetry as well as influence of nutrients from the river discharge, from the Ganges and Brahmaputra rivers (Barua *et al.* 1996; Islam *et al.* 2002). Coastal zone (Maputo Bay) for Mozambique comprises the region enclosed between latitudes of 26.5–25.5°S and longitudes of 32.5–33.5°E and is based on the coastal shelf and effects of nutrients from river discharge to the bay (Canhanga, *et al.* 2005). A more detailed description of the products, sensors, estimation algorithms, and data accuracy is available elsewhere (Martin 2004). For the selected coastal area, an average value of the radiance for each month was obtained and then aggregated to the seasonal estimate of three months.

3. Methods

3.1 Development of Satellite Water Marker

Using radiance data, a Satellite Water Marker (SWM) for predicting cholera incidence is proposed with the following functional form:

$$\text{SWM} = \left[\frac{R_{rs}(555) - R_{rs}(412)}{R_{rs}(555) + R_{rs}(412)} \right] \times 100 \quad [1]$$

where, $R_{rs}(412)$ and $R_{rs}(555)$ are satellite measured radiance at 412 nm and 555 nm, respectively. A key premise is that the variability in the difference between blue (412 nm) and green (555 nm) wavelengths determines the presence of impurity (clear to turbid) in water. This impurity can then be related to coastal water conditions associated with presence of *V. cholerae* and subsequently to cholera incidence. Clear water absorbs all colors and reflects blue (Morel and Prieur 1977; Morel *et al.* 2007). Similarly, a radiance wavelength at 555nm is dominated by green color, suggesting presence of matter, i.e., plankton, pigments and dissolved organic matter (Morel and Prieur 1977). Figure 1 provides a schematic representation of this clear-turbid spectrum within the context of SWM. A desirable property of SWM is its bounded nature of two physically meaningful end points: when water is clear $R_{rs}(555)$ approaches zero, on the other hand, when water is turbid, $R_{rs}(412)$ approaches zero. SWM values can range between -100 to 100; a value of -100 represent clear water and +100 is the turbid water with the highest content of biological matter. Cannizzaro *et al.* (2008) observed that wavelength spectra shift from blue to green as the amount of particulate matter increases from offshore to coastal waters in the Gulf of Mexico- concluding that coastal water with high chlorophyll and other biological material result in increase in the radiance value for the green wavelength. Figure 2a shows annual climatology of SWM as well as for the blue and green radiance for the coastal region of Bay of Bengal. The difference between radiance in the green (555 nm) wavelength is highest in October to lowest in June. Heavy monsoon rainfall during the months of May through July in the Bay of Bengal (Akanda *et al.* 2009) results in freshwater accumulation on the water, explaining dominance of the blue (clear) part of the spectrum, hence the difference between the blue and green wavelengths is low. Terrestrial nutrients from river discharge support plankton production including phytoplankton, zooplankton, and organic material (Lohrenz *et al.* 1990; Harding and Perry 1997; Arker *et al.* 2005) resulting in a green dominated spectrum and decrease in the blue wavelength value from October through December. If the reversal in reflectance between clear (blue color) and turbid (green color) water, as shown in Figure 1 and calculating SWM in Figure 2a, is physically plausible, then coastal water are expected to have higher green reflectance than offshore water and vice versa. This was indeed observed, as shown in Figure 2b, where autumn season reflectance for the coastal and offshore (18.0–19.0°N and 88.5–93.0°E) regions of the Bay of Bengal is shown - similar to coastal and offshore water for other oceans of the world (Morel and Prieur 1977; Cunningham *et al.* 2011).

4. Results

4.1 Relationship of SWM to cholera incidence

Cholera in the Bengal Delta has two seasonal peaks: one in spring (defined as average of March-April-May) and another in fall (defined as average of September-October-November) season (Akanda *et al.* 2009). Recent studies have indicated that seasonal and spatially asymmetric hydroclimatic conditions are associated with cholera incidence in this region (Constantin deMagny *et al.* 2008; Akanda *et al.* 2009, 2011). Low river discharge enables intrusion of bacteria laden water to inland, resulting in spring cholera peak in the coastal

areas of endemic regions. On the other hand, floods from monsoonal rainfall create environmental conditions conducive for a fall outbreak of cholera via widespread contamination of the region's water resources with cholera bacteria in suspended sediment in the flood waters (Akanda *et al.* 2009). Spring peak in the Bengal Delta is partly responsible for fall outbreaks (Akanda *et al.* 2011). A high correlation is observed between spring and fall cholera incidence ($r = 0.82$; $p < 0.05$). This correlation breaks down from preceding fall cholera to next year's spring cholera incidence ($r = 0.38$), suggesting a one-way spring-to-fall relationship (not autumn to spring) between the seasonal outbreaks (Akanda *et al.* 2011). Based on empirical observations, it is reasonable to accept that spring cholera is more closely linked with coastal processes while fall outbreak is mainly a flood dominated process. Consequently, SWM based estimation and prediction of cholera incidence is more appropriate during the spring season in the Bengal Delta. To determine relationship between SWM and spring cholera incidence, SWM values for the coastal Bay of Bengal were calculated and then seasonal correlation with cholera incidence were determined. Highest coefficient of determination (R^2), in all the twelve possible seasonal combination, between spring cholera and seasonal SWM was observed during early winter season (October-November-December -OND thereafter- $R^2 = 0.83$, $p < 0.05$). It also indicated that there is no other combination with statistically significant correlation; therefore, any other combination is not likely to yield meaningful results. High correlation between early winter SWM and spring cholera incidence provides sufficient lead time of two months for prediction before disease incidences peak and may indicate that bacterial growth is likely to be related to a range of coastal environmental conditions, and not just chlorophyll.

Consequently, simple linear regression models were developed to predict spring cholera incidence using OND SWM values (model performance statistics are shown in Table 2: Model M1). Figure 3a shows observed and predicted spring cholera incidence where the model performed satisfactorily (predicted R^2 78%; adjusted R^2 82%). Our previous studies (Jutla *et al.* 2011, 2012) have reported strong correlation of chlorophyll with spring cholera incidence in the Bengal Delta. In order to determine the predictive capability of chlorophyll for spring cholera as well as provide a comparative analysis, OND chlorophyll was used to develop a linear regression model, [Table 1: model M1(chl)]. The prediction R^2 of model M1(Chl), is 58%, which is substantially lower than model M1 that used SWM values. Therefore, it can be statistically concluded that the SWM captures a range of biological properties in the coastal waters that may not be represented in the chlorophyll algorithm.

To explore validity and broader applicability of SWM for other endemic regions, Mozambique was chosen as the test region. Seasonality of cholera in Mozambique (Maputo region) is different than Bengal delta. However, underlying mechanism of occurrence of the disease is comparable to spring cholera outbreaks in delta. As noted by Collins *et al.* (2006), majority of cholera in Mozambique is initiated along the coasts and then propagated inlands through secondary means. Here the objective was to apply the proposed methodology on Mozambique cholera data and to show applicability of SWM over a different endemic region. The analysis on hydroclimatic controls on Mozambique cholera is presented elsewhere (Collins *et al.* 2006; Jutla *et al.* 2010). A seasonal peak in the coastal region of Maputo occurs in the months of December-January-February or winter season (Jutla *et al.* 2010). For Mozambique, monthly cholera data for eleven years were available as cases of cholera observed and not as incidence. During these 11 years, the population of Mozambique increased from 17 to 22 million. The increase of population, however, is linear (World Bank, 2012); therefore, it is not likely to have significant effects on the results since the variability in the time series. Using summer (July-August-September) season SWM values, linear regression models were constructed to predict winter cholera cases in the region. Figure 3b provides validation and applicability of SWM (predicted R^2 57%; adjusted R^2 70%; Table 2, Model M2) in Mozambique region. A comparative analysis with

chlorophyll in Maputo Bay with cholera time series in Mozambique is shown in table 2, model M2(chl). It can be safely concluded that coastal chlorophyll (predicted $R^2=23\%$) has limited predictive capabilities than SWM (predicted $R^2=57\%$).

5. Discussion and Summary

Satellite radiance based index was developed to capture the variability in the coastal environmental conditions and to associate it with cholera incidence. This index is based on variability in radiance at two wavelengths, 412 nm and 555 nm, in coastal seawater. A desirable property of SWM is the bounded nature of two physically meaningful end points: when water is clear $R_{rs}(555)$ approaches zero and when water is turbid, $R_{rs}(412)$ approaches zero. Using the SWM, it was shown that prediction of cholera in coastal areas of South Asia and Southeastern Africa is conceivable with reasonable accuracy. As complementary evidence, Figure 4 shows spatial variation of SWM in the coastal Bay of Bengal during highest and lowest cholera years within the available satellite data period (1998–2010). High SWM values (Figure 4a) were observed in early winter season of 2004 prior to an epidemic in spring 2005 while low SWM values (Figure 4b) were observed in 2001 before an anomalously low cholera incidence in spring 2002; providing further evidence of the robustness of the proposed index. It should also be noted that approximately 97% of the pixels in Figure 4a (high SWM and subsequent high cholera) had higher values than in Figure 4b, suggesting a role of region-wide large scale coastal processes on cholera dynamics. The SWM has the potential functional structure to capture aggregated effects of a range of coastal environmental conditions.

The results presented here for predicting cholera incidence in two different regions using SWM are encouraging. Nevertheless, we are cognizant of limitations posed by the length of the observed satellite dataset. As more satellite data become available, the proposed approach can be further validated and refined. The idea of environmental cholera transmission was proposed in 1970s (Colwell, 1977) and continues to be refined as more observational data become available and as the roles of abiotic, biotic, and hydroclimatological factors affecting cholera transmission are clarified (e.g., Tamplin *et al.* 1990; Colwell and Huq, 1994; Lobitz *et al.* 2000). SWM estimates obtained from satellite remote sensing provide an indirect measure of coastal water conditions conducive for cholera dynamics. It cannot alone provide a direct connection to *V. cholerae* abundance, but can help determine timing and location of the presence of biological and organic matter in coastal waters that contribute to growth and distribution of cholera bacteria. These preliminary results as well as the modeling framework may provide the essential lead time to strengthen intervention efforts before outbreaks of cholera in endemic regions.

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Figure 1. Concept of Satellite Water Marker, or SWM. SWM is hypothesized as the difference between satellite measured radiance of clear and turbid water.

Figure 2.

(a) Climatology of SWM and radiances and (b) Coastal and Offshore reflectance during Autumn (OND) in the Bay of Bengal

Figure 3.

(a) Observed and predicted spring cholera incidence (%) in Bengal Delta (predicted R^2 78%; adjusted R^2 82%). (b) Observed and predicted winter cholera cases in Mozambique (predicted R^2 57%; Adjusted R^2 70%)

Figure 4. SWM during October–November–December in (a) 2004 (high cholera in spring of 2005) and (b) 2001 (low cholera in spring of 2001).

Table 1

Coefficient of determination (R^2) between cholera and SWM

	Cholera												
	SWM	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF
JFM	0.05	0.12	0.15	0.14	0.29	0.29	0.11	0.11	0.11	0.09	0.12	0.18	0.01
FMA	0.01	0.06	0.05	0.19	0.18	0.18	0.11	0.04	0.05	0.01	0.01	0.01	0.05
MAM	0.17	0.11	0.00	0.01	0.00	0.00	0.00	0.01	0.02	0.04	0.11	0.16	0.04
AMJ	0.17	0.13	0.09	0.12	0.23	0.12	0.12	0.15	0.22	0.05	0.06	0.22	0.05
MJJ	0.17	0.05	0.02	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.02	0.02	0.08
JJA	0.04	0.10	0.05	0.02	0.01	0.03	0.01	0.01	0.05	0.05	0.10	0.04	0.11
JAS	0.07	0.10	0.05	0.01	0.05	0.05	0.01	0.01	0.01	0.00	0.04	0.16	0.20
ASO	0.10	0.19	0.06	0.16	0.04	0.04	0.04	0.06	0.16	0.12	0.10	0.04	0.22
SON	0.15	0.36	0.52	0.20	0.00	0.00	0.00	0.05	0.23	0.07	0.13	0.15	0.13
OND	0.16	0.46	0.83	0.14	0.17	0.11	0.11	0.17	0.19	0.01	0.10	0.12	0.13
NDJ	0.20	0.49	0.66	0.11	0.05	0.01	0.01	0.18	0.05	0.02	0.17	0.04	0.13
DJF	0.21	0.18	0.40	0.11	0.01	0.01	0.01	0.21	0.01	0.01	0.06	0.05	0.05

Each season is defined as the average of three months where J, F, M represent January, February, March respectively. Hence, JFM= January-February-March, FMA= February-March-April and so on for all seasons.

Table 2

Model performance statistics and parameters

Model	α (intercept)	β (Slope)	Predicted R^2	Adjusted R^2	RMSE	Mean	Bias
Observed Bengal cholera incidence (%)							
M1	8.71	1.43	78%	82%	2.5%	22.30%	-
	$p<0.001$; SE=2.140						
	$p=0.002$; SE=0.204						
M1 (chl)	-16.11	19.50	58%	67%	4.32%	21.96%	0.59%
	$p=0.256$; SE=11.200						
	$p=0.020$; SE=10.32						
Observed Mozambique cholera (Cases)							
M2	-3443	520	57%	70%	350	1421 Cases	90
	$p<0.001$; SE=606						
	$p<0.001$; SE=70						
M2 (chl)	-4652	256	23%	48%	582	2512	140
	$p=0.358$; SE=1410						
	$p=0.214$; SE=99						

Model Structure: $\alpha + \beta \times \text{SWM}$; SE= Standard Error; RMSE= Root Mean Square Error; Model M1 and M1(chl)= Predicted Bengal cholera; Model M2 and M2(chl) Predicted Mozambique cholera